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Abstract: Attention helps manage the information held in visual working memory (vWM). Perceptual attention selects the stimuli to be represented in vWM, whereas internal attention prioritizes information already in vWM. In the present study we assessed the spatial precision of perceptual and internal attention in vWM. Participants encoded eight colored dots for a local-recognition test. To manipulate attention, a cue indicated the item most likely to be tested (65% validity). The cue appeared either before the onset of the memory array (precue) or during the retention interval (retrocue). The precue guides perceptual attention to gate encoding into vWM, whereas the retrocue guides internal attention to prioritize the cued item within vWM. If attentional selection is spatially imprecise, attention should be preferentially allocated to the cued location, with a gradual drop-off of attention over space to nearby uncued locations. In this case, memory for uncued locations should vary as a function of their distance from the cued location. As compared to a no-cue condition, memory was better for validly cued items but worse for uncued items. The spatial distance between the uncued and cued locations modulated the cuing costs: Items close in space to the cued location were insulated from cuing costs. The extension of this spatial proximity effect was larger for precues than for retrocues, mostly because the benefits of attention were larger for precues. These results point to similar selection principles between perceptual and internal attention and to a critical role of spatial distance in the selection of visual representations.

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Research article

The precision of spatial selection into the focus of attention in working memory

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Abstract

Attention helps to manage the information held in visual working memory (vWM). Perceptual attention selects the stimuli to be represented in vWM, whereas internal attention prioritizes information already in vWM. The present study assessed the spatial precision of perceptual and internal attention in vWM. Participants encoded eight colored dots for a local-recognition test. To manipulate attention, a cue indicated the item most likely to be tested (~65% validity). The cue appeared either before the onset of the memory array (pre-cue) or during the retention interval (retro-cue). The pre-cue guides perceptual attention to gate encoding into vWM, whereas the retro-cue guides internal attention to prioritize the cued item within vWM. If attentional selection is spatially imprecise, attention should be preferentially allocated to the cued location, with a gradual drop-off of attention over space to nearby uncued locations. In this case, memory for uncued locations should vary as a function of its distance to the cued location. Compared to a no-cue condition, memory was better for validly cued items, but worse for uncued items. The spatial distance between the uncued and the cued location modulated the cuing costs: items close in space to the cued location were insulated from cuing costs. The extension of this spatial proximity effect was larger for pre-cues than retro-cues, mostly because the benefits of attention were larger for pre-cues. These results point to similar selection principles between perceptual and internal attention, and for a critical role of spatial distance for selection of visual representations.

Keywords: spatial attention; working memory; distribution of attention; focus of attention;

Attention operates on representations of perceptual inputs – aka *perceptual attention*, and on representations sustained only in mind – aka *internal attention* (Chun, Golomb, & Turk-Browne, 2011). Here we are concerned with the operation of perceptual and internal attention on visual working memory (vWM). Perceptual attention controls which perceptual inputs get access to vWM, whereas internal attention prioritizes one over several representations simultaneously held in vWM.

There are many similarities in the effects of perceptual and internal attention on vWM. For example, Griffin and Nobre (2003) asked participants to retain four colors in vWM for a single-item recognition test. To manipulate perceptual or internal attention, one memory location was cued as likely to be tested either prior to the onset of the memory array (henceforth pre-cue) or during the maintenance phase (retro-cue). When the pre- or retro-cue was valid, responses were faster and more accurate than in a baseline condition with a non-informative cue. When the cues were invalid – i.e., an uncued item was tested – costs of cuing were observed in comparison to the baseline (see Souza & Oberauer, 2016 for a recent review). Furthermore, Nobre and colleagues have uncovered largely overlapping neural networks engaged by pre-cues and retro-cues (for a review see Gazzaley & Nobre, 2012; Lepsien & Nobre, 2006; Myers, Stokes, & Nobre, 2017), in line with the hypothesis that they operate in similar ways to prioritize information.

Here our main goal was to assess the spatial precision of perceptual and internal attentional selection within vWM as indexed by the pre-cue and retro-cue effects, respectively. Imprecise spatial selection entails that attention is preferentially allocated to one location (e.g., the cued one) with a gradual fall off over space to nearby locations. Schmidt, Vogel, Woodman, and Luck (2002) used pre-cues to show that perceptual attention in vWM spills over to nearby uncued locations. In their study, pre-cued items were remembered with a high probability, and performance in invalid pre-cue trials was better the closer the tested item was to the cued location, indicating that nearby items were also partially attended to.

This finding begs the question whether a similar effect occurs for internal attentional selection. This question can be investigated using retro-cues: if internal attention is imprecisely allocated to the retro-cued location, cuing costs for invalidly retro-cued items should also vary as a function of the spatial distance between the retro-cued item and the tested item. Imprecision in the spatial allocation of internal attention has implications for theories about the focus of attention in vWM. According to the embedded-process model (Cowan, 1999), the focus of attention can hold several items simultaneously. An imprecise focus that holds not only the one retro-cued item but also its neighbors could be assumed to be advantageous because it extends the beneficial effect of attention to those neighbors. Other theories (McElree, 2006; Oberauer, 2002) assume that the focus of attention serves as a selection device that is functionally constrained to hold a single item. Concurrent selection of multiple items would increase the chance of confusions between items, thereby undermining this selection function (see Oberauer, 2013 for a review). From this theoretical perspective we should expect that a focus of attention optimally tuned to its task is fairly precisely confined to a single item. Some accounts of the retro-cue effect also assume that the internal focus of attention is constrained to a single item (Myers et al., 2017), which can then directly assume a function of guiding action.

By using partially valid cues to guide attention before encoding (pre-cues) and before retrieval (retro-cue), we assessed whether imprecise spatial allocation of perceptual and internal attention, respectively, modulates the costs for tests of uncued items as a function of their spatial distance to the cued location. If this were the case for both pre-cues and retro-cues, this would indicate that the focus of attention is not constrained to a single item in neither case. In contrast, if this effect occurred only in the pre-cue condition, it would indicate that only perceptual attention is spatially imprecise, but internal attention is not.

Experiment 1

Method

Participants

Sixty students (18 to 35 years old) of the University of Zurich took part in two 1-hour sessions in exchange for course credit or 30 CHF. Participants were evenly split into two groups, receiving two experimental versions (Experiment 1a and 1b) that differed only regarding the time to encode the memoranda. For all experiments reported here, participants read and signed an informed consent form prior to testing, and they were debriefed at the end. The experimental protocol was in accordance with the ethical regulations of the Faculty of Arts and Social Sciences of the University of Zurich.

Materials and Procedure

The experiments were programmed using the Psychophysics Toolbox 3 (Brainard, 1997) implemented in Matlab. Participants were tested in individual booths, where they sat approximately 50 cm away from the computer screen (viewing distance was unconstrained).

Participants completed a color-recognition task with a cuing manipulation (pre-cue, retro-cue, or no-cue). In the no-cue condition (see Figure 1), each trial started with a white fixation cross presented against a grey background (0.5 s). Next, eight colored dots (radius 0.83°) were shown for 1 s (Experiment 1a) or 0.1 s (as used by Schmidt et al., 2002; Experiment 1b). The memoranda were randomly sampled from a set of 12 colors (beige, yellow, light green, dark green, light blue, dark blue, purple, magenta, brown, red, orange, and black). The dots were evenly spaced along an invisible circle (radius 5°) centered on the middle of the screen. A blank screen was shown after array offset (1 s; retention interval), followed by the presentation of a test stimulus in one of the memory locations until a response was given. Participants judged whether the test stimulus had the same color as the memory item that had appeared in that location: they pressed the left or the right arrow key to indicate a positive or negative response, respectively. A positive (matching) test-stimulus was shown in 50% of the trials. Negative test-stimuli were of two types: a color not presented in the memory array (new probe, 25% of the trials), or a color shown in another position than the tested one (intrusion probe). After the response, visual feedback regarding the correctness of the response was presented for 0.5 s. The next trial started after a 1.5-s blank interval.

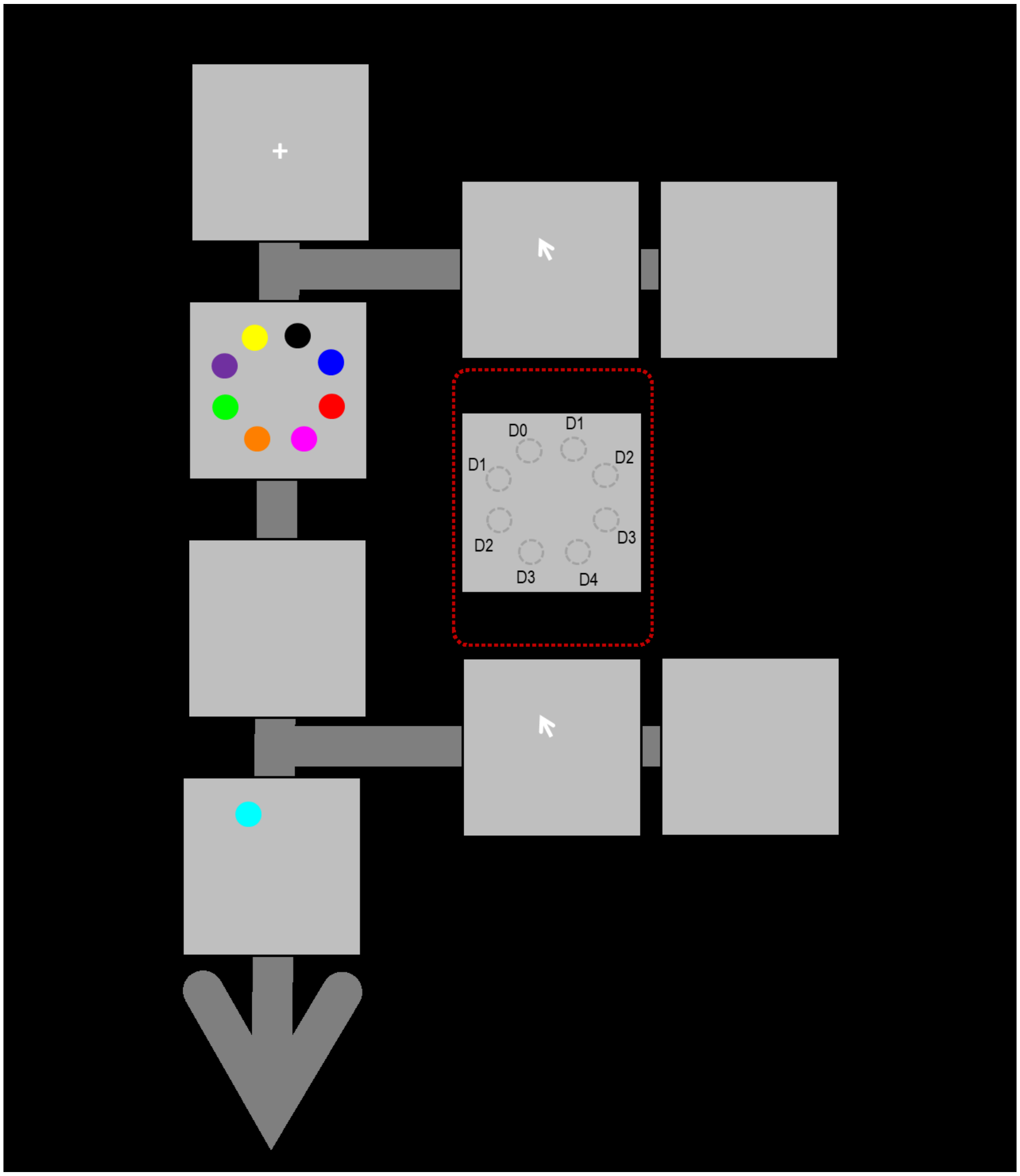

Figure 1. Illustration of the flow of events in no-cue trials. Pre-cue and retro-cue trials only differed from no-cue trials in terms of the presentation of the cue and of the blank interval before encoding or before the memory test, respectively. The red dotted line inset illustrates the spatial distance between the cued item (D0) and the remaining memory items (D1-D4, in steps of 45°) in both cue conditions.

Pre-cue trials only differed from no-cue trials in that the fixation-cross was followed by the presentation (0.1 s) of a white arrow pointing to the location of one of the upcoming memory items, and the memory array was shown 1 s thereafter. Retro-cue trials, in contrast, only differed from no-cue trials regarding the events unfolding before the test: After the 1-s retention, a white arrow (0.1 s) pointed to one of the memory locations, and the test-stimulus was shown 1 s thereafter. The 1-s post-cue interval in both cuing conditions was included to provide ample time for attention to be focused on the cued location. The cues were valid in 65% of the trials. In the remaining trials, one of the uncued items was tested. The distance between the cued (hereafter D0) and uncued items was varied in four steps (D1-D4), as indicated in the inset in Figure 1, with D1 being the closest location to the cued one (45° away), and D4 being the location 180° away.

Across the two experimental sessions, participants completed a total of 800 trials: 320 pre-cue trials, 320 retro-cue trials, and 160 no-cue trials. From the 320 cue trials, 208 were valid trials and 112 invalid ones. In invalid-cue trials, items at distances 1-4 were equally likely to be tested (yielding 28 trials per distance). In the beginning of the experiment, participants were instructed about the three trial types (no-cue, pre-cue, and retro-cue), and told that the cues would indicate the test item in the majority of the trials. They were further instructed to repeat continuously aloud “der-die-das” to prevent use of verbal memory.

Data Analysis

We submitted our data to a Bayesian Analysis of Variance, ANOVA (Rouder, Morey, Speckman, & Province, 2012) using the BayesFactor package (Morey & Rouder, 2015) for R (R core team, 2014). The Bayesian ANOVA computes the strength of the evidence in the data in favor of including or omitting an effect of interest. The relative evidence for one model over another is the Bayes Factor (BF). In the present article, BFs above 1 indicate that the data is more likely under the alternative hypothesis, whereas BFs below 1 indicate that the data is more likely under the null hypothesis. It is common to consider BFs between 0.33 and 3 as weak evidence in favor of a hypothesis, whereas BFs below 0.10 or above 10 are considered as strong support for the null or the alternative hypothesis, respectively.

In addition, we analyzed the data with a hierarchical Bayesian logistic regression model, which has the advantage of using the accuracy of each trial as dependent variable as opposed to proportion of correct responses aggregated within each design cell. The same pattern of results was obtained (see Online Supplementary Material).

The data and analysis scripts for all experiments reported here and in the Supplementary Material are available at the Open Science Framework: https://osf.io/vz89r/?view_only=a74509c719b44bf296dc00642432d5dc

Results

Figure 2A shows the proportion of correct responses as a function of cue condition and spatial distance between cued and tested item, separately for each experimental version.

Valid-Cue Benefits

To assess valid-cue benefits, we entered in two separate ANOVAs the factors of cue condition (no-cue vs. valid pre-cue; or no-cue vs. valid retro-cue) and experimental version (1a vs. 1b) which involve only a difference in encoding time. Valid pre-cues improved accuracy compared to no-cue trials ($BF_{10} = 1.9 \times 10^{27}$). Experimental version had no effect ($BF_{10} = 0.22$), however there was weak evidence for a valid pre-cue x experiment interaction ($BF_{10} = 2.55$) due to the somewhat larger valid pre-cue benefit in E1b. Likewise, valid retro-cues improved accuracy ($BF_{10} = 1.4 \times 10^9$). There was weak evidence against a main effect of experiment ($BF_{10} = 0.55$), and against a valid retro-cue x experiment interaction ($BF_{10} = 0.44$). Lastly, we compared the size of the cuing benefits with a t-test, which provided overwhelming support ($BF_{10} = 3.66 \times 10^{17}$) for a larger pre-cue benefit compared to the retro-cue benefit.

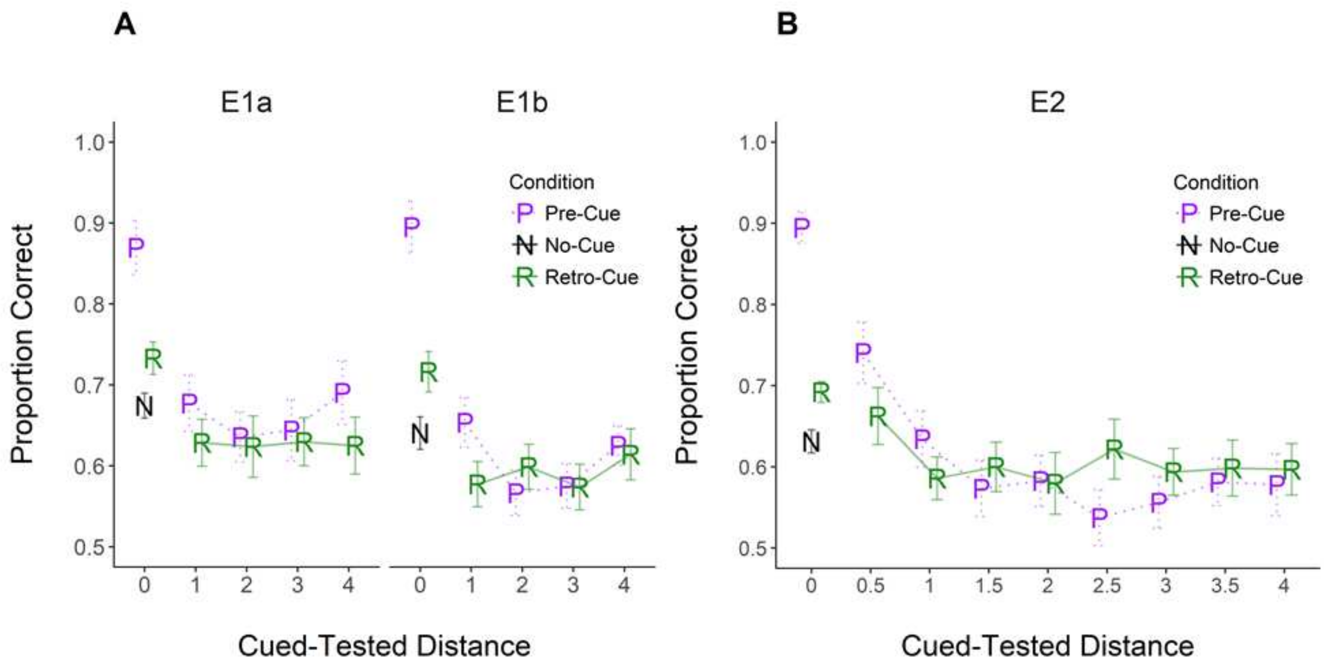

Figure 2. Proportion of correct responses in each experimental condition as a function of the spatial distance (bin = 45°) between the cued and the tested item location. Panel A. Data of Experiments 1a and 1b (min. distance = 45°). Panel B. Data of Experiment 2 (min. distance = 22.5°). *Note.* In the no-cue condition, no cue was presented before the test, hence we classified it as a distance of 0. Error-bars depict 95% within-subjects confidence intervals (Morey, 2008).

Invalid-Cue Costs

To assess invalid cuing costs (across all distances), we conducted two ANOVAs entering cue condition (no-cue vs. invalid pre-cue; or no-cue vs. invalid retro-cue) and experiment as factors. There was evidence for an invalid pre-cue cost ($BF_{10} = 6.77$), for an effect of experiment ($BF_{10} = 3.05$), with weak evidence against their interaction ($BF_{10} = 0.56$). The effect of experiment reflects the somewhat lower levels of performance in Experiment 1b (shorter encoding time). There was very strong evidence for invalid retro-cue costs (BF_{10} = 46370), ambiguous evidence for a main effect of experiment (BF_{10} = 1.49), but no interaction between them (BF_{10} = 0.28). Overall, the comparison of the size of cuing costs between cue types showed support for smaller costs with pre-cues than retro-cues (BF_{10} = 10).

Spatial Distance Effect

Our main question was regarding a modulation of invalid cuing effects by the spatial distance between the cued and the uncued-tested location, and whether this effect differs depending on cue type. For this, we took only invalidly cued trials and assessed the effects of spatial distance, cue condition (pre-cue vs. retro-cue), experiment, and their interaction. The best model (BF_{10} = 1736.5) included the effects of spatial distance, cue condition, and experiment, and also the distance x cue interaction. Critically, inclusion of the distance x cue interaction was supported by BF_{10} = 4.71, reflecting the fact that cuing costs only varied with spatial distance in the pre-cue condition. To get to the bottom of this interaction, we assessed the evidence for a spatial distance effect in each cue-condition separately. There was strong evidence against an effect of spatial distance in the retro-cue condition (BF_{10} = 0.04). Conversely, in the pre-cue condition this effect was strongly supported (BF_{10} = 970).

Figure 2A suggests that the modulation of cuing costs by distance is mainly due to items at D1 (45° away) being insulated from cuing costs in the pre-cue condition. When considering only this distance, a t-test showed no evidence for a pre-cue cost (BF_{10} = 0.09), but overwhelming support for a retro-cue cost (BF_{10} = 3940).

Discussion

Experiment 1 showed that objects in the vicinity of the cued location were insulated from cuing costs in the pre-cue but not the retro-cue condition, suggesting that perceptual and internal attention differ in spatial imprecision. There is one caveat, though: The pre-cue effect was much larger than the retro-cue effect. It is, therefore, possible that the observed interaction reflects a scaling artifact. To address this issue, we modelled the data of the two cue conditions with a hierarchical Bayesian exponential model assuming that the accuracy (in logit scale) decreases exponentially with the cued-tested spatial distance (0 to 3) [1]. The exponential is described by three parameters: (1) the asymptote, which here reflects the cueing costs at far locations; (2) the intercept reflecting the strength of the cueing effect at distance 0; and (3) the rate of change as function of spatial distance. The general form of our model was as follows:

$$\text{Logit}(\text{accuracy}_{t,p,c,e}) = \text{Asymptote}_{p,e} + \text{Intercept}_{p,c,e} \times \exp(-\text{Rate}_c \times \text{Distance})$$

with t standing for trial, p for participant, c for cue, and e for experiment. Critically, we built two models that differed only regarding whether we included an effect of cue condition on the rate parameter (two-rate model) or not (one-rate model; see model and results in the OSF).

The two-rate model estimated a slightly higher rate of decrease in accuracy over distance for the retro-cue compared to the pre-cue condition, but this difference was not credibly different from zero (BF_{10} = 0.70; see Figure 3). We also compared the fit of the one-rate vs. two-rate model using DIC (Deviance Information Criterion), a metric for comparison of hierarchical Bayesian models. The one-rate model had a slightly lower DIC (2560.6) than the two-rate model (2566.8), which is indicative of a better fit. Hence, all in all, the data of

[1] We excluded distance 4 (180°) because there was a tendency for increase in accuracy in the pre-cue condition at this distance that could distort the fitting of the exponential model.

Experiment 1 seems ambiguous regarding a difference in the rate of spatial imprecision across cue conditions.

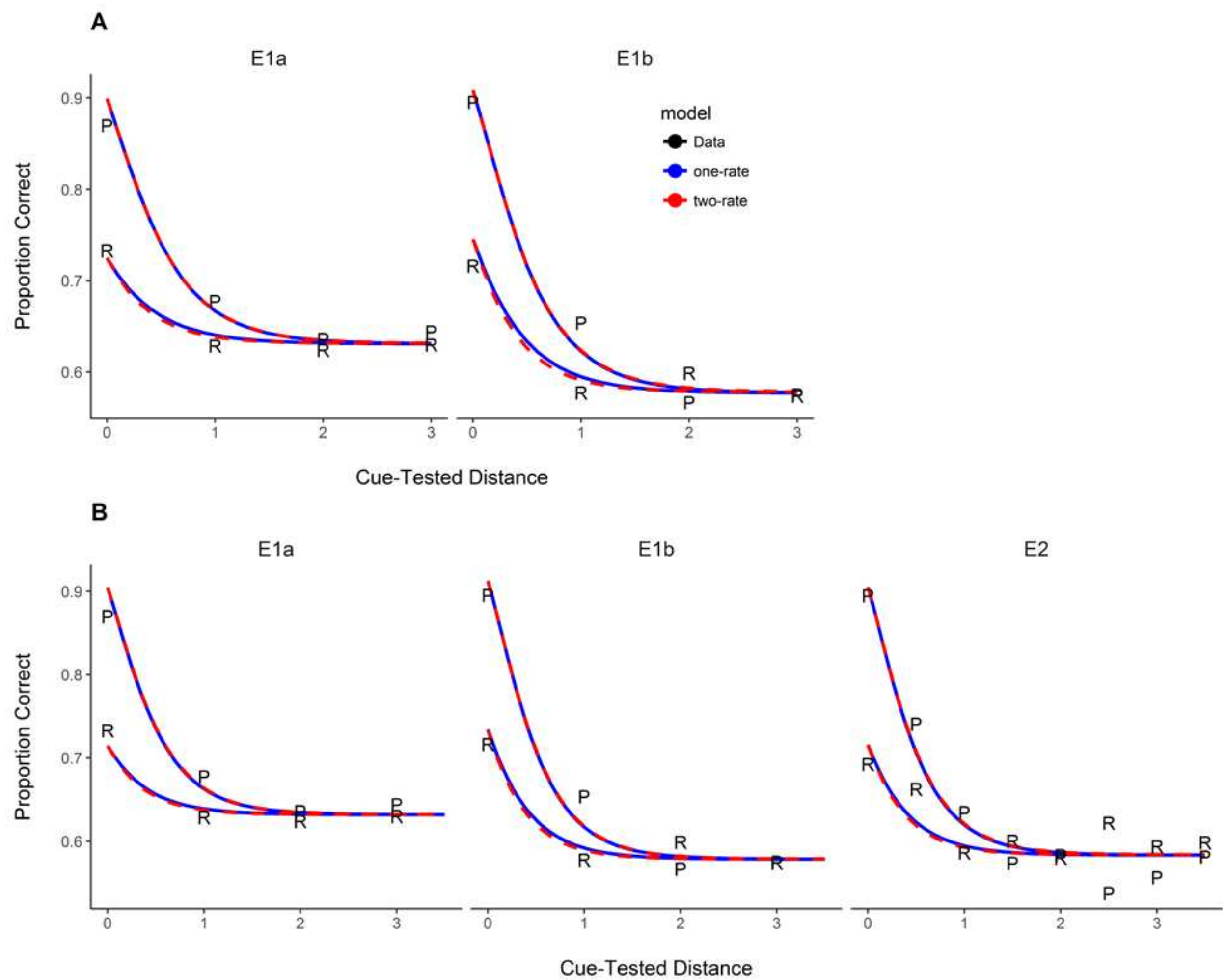

Figure 3. Predictions of the exponential models (lines) plotted alongside the data (letters: P for pre-cue, R for retro-cue) in each experiment. Panel A shows the predictions of the models fitted simultaneously to the data of Experiments 1a and 1b. Panel B shows the predictions of the model fitted simultaneously to the data of Experiments 1a, 1b, and 2.

Experiment 2

The exponential modeling of Experiment 1 provided weak evidence against an effect of cue type on the rate of spatial imprecision. The predictions in Figure 3A suggest, however, that we may be able to clarify whether the two cue conditions differ in rate by obtaining a more fine-grained measure of the spatial gradient. Hence in Experiment 2, we doubled the number of possible spatial locations for the memoranda, thereby reducing the size of the smallest separation between items to 22.5° (instead of 45°). By doing so, we increased the resolution of our measurement of the spatial gradient. If allocation of attention in the retro-cue is also spatially imprecise, we should observe that items at the closest location to the cued one are now spared from cuing costs, akin to the observation for pre-cues.

Method

Participants and Procedure

Forty students took part in Experiment 2. The procedure was the same as in Experiment 1b with three exceptions. First, we increased the number of possible memory locations from 8 to 16, thereby reducing the minimal distance between every two items to 22.5°. Second, for every trial, we randomly selected half of the locations to be occupied by memory items. Third, the cues were valid in 60% of the trials (192 of 320 trials), and the invalid-cue trials were evenly distributed across the 8 spatial distances (22.5° to 180° in steps of 22.5° degrees), yielding 16 trials per distance.

Results

Figure 2B shows accuracy as a function of spatial distance in Experiment 2. For better comparability across experiments, we also binned distances in steps of 45°. Our main interest was in the observation of cuing costs for neighboring items (D0.5 and D1). There was strong evidence against cuing costs at the smallest spatial distance (D0.5: 22.5°) both in the pre-cue (BF_{10} = 0.02) and retro-cue (BF_{10} = 0.07) conditions. At a distance of 45° (D1), only the pre-cue condition showed evidence against cuing costs (BF_{10} = 0.15), whereas the evidence for a retro-cue cost was strong (BF_{10} = 28.8), replicating the results of Experiment 1. Modeling of the data of the three experiments together (see Figure 3B) with the exponential function showed evidence against a difference in the rate parameter across cue conditions (BF_{10} = 0.36), and the one-rate model had a better fit (DIC = 5375.8) than the two-rate model (DIC = 5388.6).

Discussion

Experiment 2 showed that the spatial imprecision in the two cue conditions, when measured as the rate of an exponential drop-off of accuracy, is similar. When the minimum distance between items was reduced, we were able to measure a spread of the retro-cue effect to nearby locations. These results indicate that the two cue conditions differ mainly in the strength of the cueing effect, but not in their selectivity over space.

General Discussion

We guided perceptual attention to gate encoding into vWM using pre-cues, and we guided internal attention to modulate retrieval from vWM using retro-cues. In both cases, the cues were only partially valid, such that in some proportion of trials, uncued items were also tested. Our main aim was to assess whether performance for uncued items varies as a function of their spatial distance to the cued location. If attentional allocation is spatially imprecise, then items in the vicinity of the cued location are also partially attended to, and memory for these items should be better than for items farther away. Previous research has shown that this is the case for the allocation of perceptual attention to gate encoding into vWM (Schmidt et al., 2002). Here, we addressed the question whether internal attentional selection from vWM is also imprecise, such that when participants attempt to select one vWM content, they also partially select other items at nearby locations. Experiment 1 initially pointed to differences in the way spatial attention was allocated to the cued locations: the retro-cue effect did not spill over to nearby locations, whereas the pre-cue effect did. Modeling of the data, however, pointed to the possibility that the measurement of the rate of spatial imprecision in the proportion-correct scale is confounded by strength of the attentional benefit. To bypass this limitation, we reduced the spatial distance between items by half (22.5°, Experiment 2), which then allowed us to also observe a neighbor-sparing effect in the retro-cue condition. These results indicate that the metric distance between items (separation in space) rather than ordinal separation (neighbors vs. non-neighbors) is critical in the spatial allocation of attention in both domains.

One may wonder whether the appearance of a steeper spatial gradient for retro-cues in Experiment 1 could be minimized under a lower memory load. To answer this question, we ran an additional experiment (see Online Supplementary Material) in which we varied memory load (2, 4, or 8 items; min. spatial distance of 45°), and the presence of a retro-cue vs. no cue. There were clear memory load effects, valid retro-cue benefits, and invalid retro-cue costs. In line with Experiment 1, we found no evidence supporting a spillover of internal attention to locations 45° away in the circle for any level of memory load.

Many studies have pointed to similarities in the way in which perceptual and internal attention operates on vWM representations (Gazzaley & Nobre, 2012; Griffin & Nobre, 2003; Sahan, Verguts, Boehler, Pourtois, & Fias, 2016). Some other studies, however, have pointed to dissociations. For example, Makovski and Jiang (2007) showed that spatial cuing of multiple items simultaneously was beneficial in the case of pre-cues but not retro-cues, and Tanoue and Berryhill (2012) showed that allocation of perceptual attention through pre-cues depends on the eccentricity of the objects, but this was not the case for retro-cues. With regard to the precision of spatial allocation, our data suggests that both perceptual and internal attention spread along the same spatial gradient. Given that the benefits of internal attention are smaller compared to perceptual attention, the distance over which the cueing effect spreads in the retro-cue condition is, however, reduced.

Our results indicate that selection of representations in vWM is not tightly constrained to one item's spatial location. One interpretation of this result is that the focus of attention in working memory sometimes selects two spatially close items simultaneously. This would raise their chance of being encoded (when pre-cued) or retrieved (when retro-cued), but at the same time might raise their chance of being confused with each other. Other studies (Bays, 2016; Emrich & Ferber, 2012; Oberauer & Lin, 2017; Rerko, Oberauer, & Lin, 2014; Sahan et al., 2016) have shown that the degree of spatial overlap between items increases the likelihood of these items being confused with each other (binding error). Attending to them simultaneously would raise the accessibility of both, thereby raising the chance of confusing the target with its close neighbor at test – this would diminish the cueing benefit. An alternative interpretation of the present findings is that, on each trial, only one item is selected by attention, and the spatial gradient reflects the probability of mis-selection: On some trials participants attend not to the cued item but its close neighbor. In this scenario, only one item is attended to at any time, and the problem of an increased chance of confusion does not arise.

References

Bays, P. M. (2016). Evaluating and excluding swap errors in analogue tests of working memory. *Scientific Reports*, *6*, 19203.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436.

Chun, M. M., Golomb, J. D., & Turk-Browne, N. B. (2011). A taxonomy of external and internal attention. *Annual Review of Psychology*, *62*, 73–101.

Cowan, N. (1999). An embedded-process model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 62–101). New York, NY: Cambridge University Press.

Emrich, S. M., & Ferber, S. (2012). Competition increases binding errors in visual working memory. *Journal of Vision*, *12*, 12.

Gazzaley, A., & Nobre, A. C. (2012). Top-down modulation: bridging selective attention and working memory. *Trends in Cognitive Sciences*, *16*, 129–135.

Griffin, I. C., & Nobre, A. C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience*, *15*, 1176–1194.

Lepsien, J., & Nobre, A. C. (2006). Cognitive control of attention in the human brain: Insights from orienting attention to mental representations. *Brain Research*, *1105*, 20–31.

Makovski, T., & Jiang, Y. (2007). Distributing versus focusing attention in visual short-term memory. *Psychonomic Bulletin & Review*, *14*, 1072–1078.

McElree, B. (2006). Accessing Recent Events, *46*, 155–200.

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Reason*, *4*, 61–64.

Morey, R. D., & Rouder, J. N. (2014). BayesFactor: Computation of Bayes factors for common designs (Version 0.9.9). Retrieved from http://CRAN.R-project.org/package=BayesFactor

Myers, N. E., Stokes, M. G., & Nobre, A. C. (2017). Prioritizing Information during Working Memory: Beyond Sustained Internal Attention. *Trends in Cognitive Sciences*, *21*, 449–461.

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *28*, 411–421.

Oberauer, K. (2013). The focus of attention in working memory: From metaphors to mechanisms. *Frontiers in Human Neuroscience*, *7*. doi:10.3389/fnhum.2013.00673

Oberauer, K., & Lin, H.-Y. (2017). An interference model of visual working memory. *Psychological Review*, *124*, 21–59.

R core team. (2014). *R: A language and environment for statistical computing*. Vienna: Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Rerko, L., Oberauer, K., & Lin, H.-Y. (2014). Spatial transposition gradients in visual working memory. *The Quarterly Journal of Experimental Psychology*, *67*, 3–15.

Rouder, J. N., Morey, R. D., Speckman, P. L., & Province, J. M. (2012). Default Bayes factors for ANOVA designs. *Journal of Mathematical Psychology*, *56*, 356–374.

Sahan, M. I., Verguts, T., Boehler, C. N., Pourtois, G., & Fias, W. (2016). Paying attention to working memory: Similarities in the spatial distribution of attention in mental and physical space. *Psychonomic Bulletin & Review*, *23*, 1190–1197.

Schmidt, B. K., Vogel, E. K., Woodman, G. F., & Luck, S. J. (2002). Voluntary and automatic attentional control of visual working memory. *Perception & Psychophysics*, *64*, 754–763.

Souza, A. S., & Oberauer, K. (2016). In search of the focus of attention in working memory: 13 years of the retro-cue effect. *Attention, Perception, & Psychophysics*, *78*, 1839–1860.

Tanoue, R. T., & Berryhill, M. E. (2012). The mental wormhole: Internal attention shifts without regard for distance. *Attention, Perception, & Psychophysics*, *74*, 1199–1215.